Waterproofing sprayed concrete tunnels

In this article, Dr Benoît Jones, Tunnelling and Underground Space MSc Course Manager at the University of Warwick, looks at the underlying mechanisms behind waterproofing design philosophies for sprayed concrete tunnels

MOST THINGS ARE a little more complicated than they first appear. And complicated things are interesting. If you don't agree, best put this magazine down now and go get a different job because you clearly aren't suited to tunnelling.

In the last issue of Tunnelling Journal, Andy Pickett and Alun Thomas laid out a smörgåsbord of design philosophies for sprayed concrete linings past, present and possibly future. One thing all the philosophies had in common was that where there was a waterproof membrane, either sprayed or sheet, the water pressure was assumed to act on the back of the membrane, and this pressure was assumed to be transferred to the secondary concrete lining, whether sprayed or cast in situ. This is because the membrane is either considered impermeable or at least a couple of orders of magnitude less permeable than the concrete, and therefore a water pressure within the concrete will tend to be applied to the membrane. There is nothing really wrong with these assumptions, but it is interesting to ask what might actually be occurring, partly because it is complicated (and hence interesting), and partly because we can then question whether these design assumptions and philosophies bear any relation to what we think may be the reality.

Unpicking the design philosophies

It is clear that for a sheet waterproof membrane system not bonded to the primary lining and with a geotextile fleece behind the PVC sheet, any leakage of water through cracks in the primary lining will eventually spread around the sheet membrane and apply a hydrostatic pressure to the secondary lining. Therefore, it seems reasonable to design the secondary lining to support all of the groundwater pressure. For a sprayed waterproof membrane, it is not so obvious that this is the case, because the membrane is bonded to the primary lining. Bond strengths quoted by suppliers are up to 1.5MPa. Therefore, water passes through cracks in the concrete and applies pressure to the back of the membrane, but only over the area of the crack plus a small distance either side (due to local debonding to allow crack bridging to occur). Therefore, the forces exerted on a secondary lining due to the groundwater pressure over these small areas would be tiny, or to use a technical term, ickle.

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So for a sprayed waterproof membrane, the water would need to penetrate through the full thickness of intact sprayed concrete in order to apply pressure to the whole membrane and make the secondary lining earn its keep. But a good quality modern sprayed concrete has quite a high strength and a low porosity, and usually contains cement replacements such as microsilica, and superplasticisers, which serve to make concrete less permeable. Therefore, permeability will probably be lower than 10^{-12}m/s, and quite possibly less than 10^{-13}m/s. What does permeation of water through such a nigh-on impermeable material look like? And how long will it take for groundwater to reach the membrane?

Tests to determine permeability of sprayed concrete

Permeability can be calculated by applying a pressure gradient to a saturated specimen, waiting for a steady-state to be established and then measuring the flow. For good quality concrete with a permeability of 10^{-12}m/s or less, permeation tests become impractical because the flow quantities to be measured are so small, and the errors introduced by very small leaks, mechanical deformation of the concrete or apparatus under pressure and absorption by seals can affect the results (Concrete Society, 2008). Therefore, permeability testing usually consists of a penetration test to EN 12390-8:2009. Here water is applied under pressure to a 75mm diameter circular area on one face of a cube or cylinder with a minimum dimension on that face of 150mm. After 72 hours the specimen is split open and the penetration measured. This means the flow is approximately uniaxial as long as water doesn't reach the sides of the specimen. Since the hydraulic gradient decreases as the penetration front moves into the concrete, Valenta (1970) came up with an equation to relate the uniaxial penetration of water into concrete to time:

$$d = \sqrt{\frac{2Kth}{v}}$$

where d is the depth of penetration at time *t*, *K* is the permeability in m/s, *h* is the pressure head in m and *v* is the porosity of the concrete. The penetration is proportional to the square root of time, and this means the rate of penetration decreases with time. This relationship was corroborated by tests performed by Browne & Domone (1975), which are shown in Figure 1. Contrary to usual practice, the data is not presented in log scale so that the true decay of penetration with time can be appreciated.

But how does this penetration permeability test relate to intrinsic steady-state flow permeability? Luckily, in this case it doesn't have to, because what we are really interested in is penetration, i.e. how long the groundwater takes to get to the membrane and apply a pressure. Once it gets there, the water stops if the membrane is doing its job, so steady-state flow never occurs.

Figure 2 shows curves based on Valenta's equation with a porosity of 0.3 and an applied pressure head of 20m for three different values of permeability. Plotting these curves over 500 years should be cautiously undertaken since we obviously do not have experimental data to validate them. However, they suggest that during the design life of the tunnel and for typical sprayed concrete permeability values the groundwater may never even reach the waterproof membrane let alone exert pressure on it (except at tiny crack locations). If longer-term penetration test data were available, a maximum sprayed concrete permeability could be specified for a project to ensure the groundwater won't penetrate to the membrane over the design life of the lining system. Maximum permeability is often specified for durability reasons, for example on the Jubilee Line Extension project the maximum permeability specified for the precast concrete segments was 10^{-13}m/s, and the standard deviation of over 2000 measurements was only 3.9 x 10^{-14}m/s (Cabrera, 1997). It is also often a standard test on larger sprayed concrete projects. Installation of a secondary lining designed for the full hydrostatic water pressure could then be postponed for 200 years or so.

Figure 1: Penetration of seawater into concrete under 70m pressure head, data from Browne & Domone (1975)

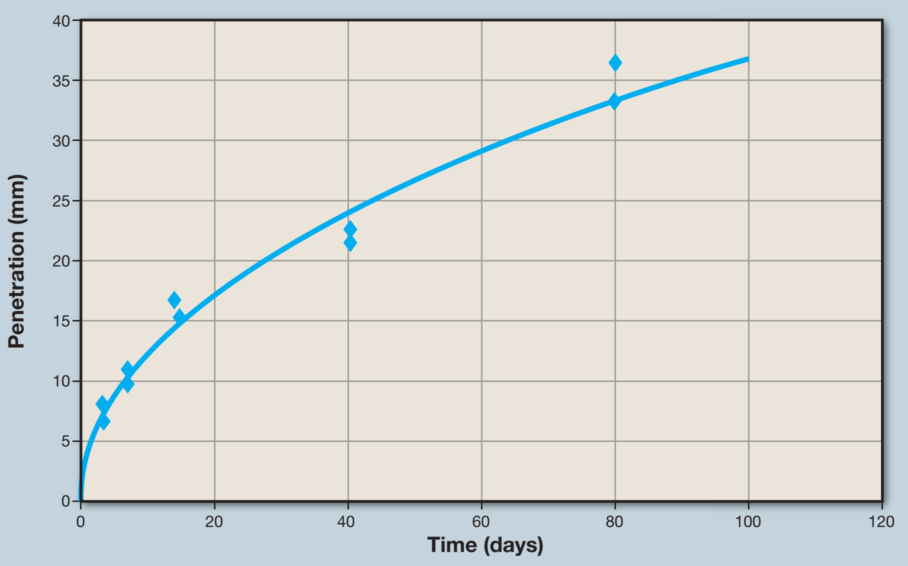
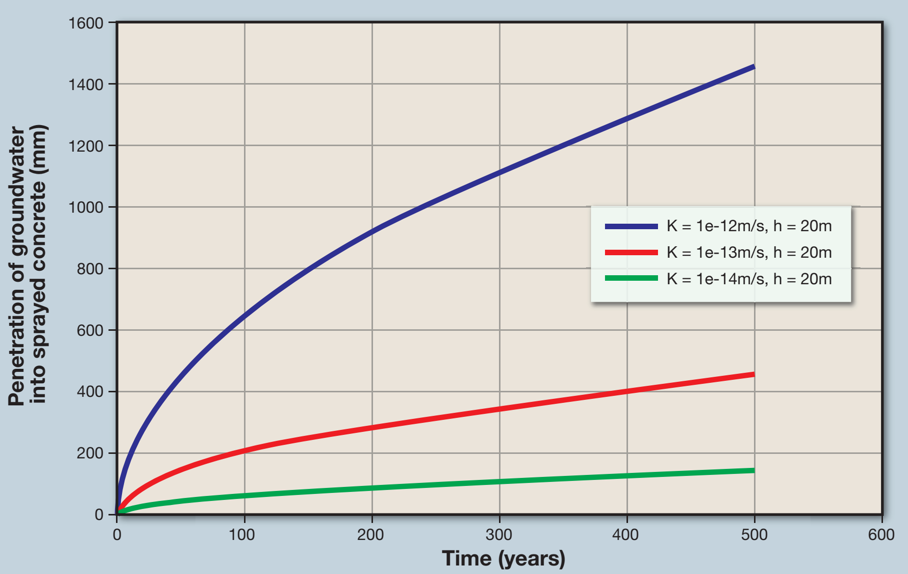


Figure 2: Projections of Valenta's penetration equation into the long-term



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ACKNOWLEDGEMENTS

Some of these ideas were inspired by a conversation with Normet's Ross Dimmock.

CORRECTION

In Benoît's article in the last issue, entitled 'A Loaded Question', the labels on the graph were accidentally switched in production. The light blue line should have been labelled 'elastic soil' and the dark blue 'non-linear elastic soil'